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On the applicability of the visual impact assessment OAI_{SPP} tool to photovoltaic plants

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ABSTRACT

Among the technologies of exploitation of renewable energy sources, solar photovoltaic plants and wind power plants are the ones who had the highest growth rate and in the future may contribute substantially to meeting energy demand and requests for production of carbon-free energy. However, it was also shown that even though there is a considerable support for policies promoting renewable energy at a general level, local communities often perceive the installation of systems powered by renewable sources such as limiting the quality of life, or impacting on the natural and built landscape. Consequently, the studies concerning the procedures for assessing the territorial and landscape impacts of this type of systems have recently seen a remarkable development.

If an extensive scientific literature is now available regarding the assessment of visual impact of wind turbines, with applications in several countries, there are few studies, theoretical or applied, dealing with the visual impact of photovoltaic plants, which represent, also for their physical size, an important form of transformation of the agricultural and forestry land.

As part of studies conducted by the authors regarding the territorial impacts of photovoltaic plant, in this paper, a procedure to evaluate the visual impact of a PV plant based on a quantitative indicator and that was published in the same journal (vol. 13, no. 5, p. 986–99) is adopted and discussed with reference to the application on some case studies. As a result, some modifications to the procedure are presented and a discussion on how this procedure may be used and integrated into the administrative requirements of large and small scale PV plants developments is carried out. From the results, it can be derived that such a procedure can be effectively used provided that a regulatory framework is set by the local authority that carries out the authorizaion procedures.

Contents

1. Introduction

Although at a general level there is a considerable support for policies promoting the use of renewable energy, local communities often perceive that the installation of renewable power plants may limit the quality of life or impact on the natural landscape and the built environment [1]. This is why a new research field that was called "social acceptability of renewable energy" is currently under development on many different aspects (e.g. psychological and perceptual, spatial, economic). A general introduction to this subject, which is eminently interdisciplinary, was provided by Wüstenhagen et al. [2].

In particular, in Italy and in Europe, the case of the photovoltaic (PV) plants is rather peculiar: this sector has undergone a remarkable growth because of the regulatory incentives (in Italy the DM 19 February 2007 feed-in law was renewed for the period

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2011–2013). The growth in the demand of authorization for the developments of these plants was followed by a bureaucratic simplification, but the administrative proceeding can last, in some cases, up to a year, as a function of a landscape constraint. This is one of the reasons why in this paper the tools that can be adopted to perform an objective judgment of the visual compatibility of this type of plants are analyzed.

In fact, private investors increasingly are having to cope with stringent requirements of local authorities on the criteria required to be met by the PV plants, while at the same time local authorities are in the need to govern the diffusion of photovoltaic technology on their territory – especially in case of rural sites, mountain and historic or artistic sites – through guidelines, regulations, and addenda to the building construction rules. That is why it is desirable that through dedicated research activities, increasingly sophisticated and reliable tools for assessing the visual and landscape compatibility of photovoltaic plants may be provided.

To this regard, a classification of the territorial and landscape impacts of the photovoltaic technology, in particular the ground mounted plants, which are the most impacting on the territory, was provided in a contribution by Chiabrando et al. [3]. In that work, the problem of glare caused by reflection of sunlight by the surface of the panels, a particularly significant problem in the case of complex land morphologies, as hilly or mountainous areas, or near sensitive infrastructures, as roads and airports, was later investigated.

In this work, the existing methodologies for the assessment of renewable power plants, although not specifically relating to solar, and the applications that can be conducted through them in the field of solar photovoltaics, are presented and discussed both from the theoretical and applied points of views. One of the most recently proposed tool, the OAI_{SSP} [4], is analyzed and discussed by means of the application to some case studies. Some modifications to the procedure are proposed and the application to the authorization procedures is later discussed.

2. Methods and tools

A first work that considered the territorial impacts of the solar powered plants was the one of Tsoutsos et al. [5] where, for the solar photovoltaics, the land use, reduction of cultivable land and visual impacts (called "visual intrusion-aesthetics") were identified. Beyond the illustration of generic mitigation measures, a description of the tools that can be adopted for conducting the assessments of such impacts is not present in that work, and with respect to the visual impact a "careful system design" and an "integration within the structural components of buildings" are recommended. An examination of the impacts related to the photovoltaic systems, especially the ground mounted ones, was conducted in a paper [3] and includes, among others, a visual impact on the components of the landscape. However, at international level it is not clearly identified how the assessment of such impacts should be conducted and what tools should be used.

This is unlike the case of the wind turbines visual impact, about which there is a wide established literature on procedures and case studies, also mutually validated between the various authors. A first methodological contribution, applied to a case study, on the evaluation of the visual impact of wind turbines is the one of Hurtado et al. [6], later applied by Tsoutsos et al. [7]; further contributions came from Möller [8], Bishop and Miller [9], Torres Sibille et al. [10], Ladenburg [11] and Rodrigues [12]. Furthermore, Bishop worked, from the theoretical point of view, on the detection thresholds of visual recognition of the impacts on the landscape [13], with practical applications to the case of wind turbines [14].

From a critical analysis of the various studies, two families of landscape impact assessment methodologies that, by extension from other fields, can be applied to the case of photovoltaic systems can be identified. These are:

- a first one, of a punctual type, that is conducted through the analysis of real photographic images or visual simulations;
- a second one, of an extensive type, that is conducted by identifying some visibility indexes of the plant over a vast territory.

The first type of analysis is illustrated in the next section and takes into account not only the visibility of the plant but also other aspects of the perception that are more difficult to measure, such as the shape and colour of the artefacts. The second type of analysis, applied by Hurtado et al. [6], Möller [8] and Tsoutsos et al. [7] in the case of wind turbines as well as by Rogge et al. [15] in the case of agricultural greenhouses, is based on a discretization of the territory that may potentially be impacted by the artefact and on the determination of indices of impact on the landscape – usually but not exclusively, of vision – for each unit of land, that are weighted as a function of, e.g. the population density of each portion of land. These types of assessments are usually conducted through a GIS application, with the related spatial analysis tools.

2.1. The visual quality assessment through pictures

The technique of visual quality assessment of the landscape that makes use of photographic pictures comes under the visual simulation techniques for assessing the compatibility of landscaping projects [16]. This technique was widely used for assessing the visual quality of the countryside [17], even though it is influenced, as shown by Senes and Toccolini [18], by the conditions at the moment the picture was taken, especially with respect to the weather.

In this work, the study of a Spanish research group [4] on the objective assessment of the aesthetic impact of solar systems through evaluation of photographic images was taken as a reference and applied to some extent. This is the only published work on the objective visual impact of solar panels. The indicator of aesthetic impact of a solar panel (it could be both solar thermal or photovoltaic) is expressed through the continuous parameter OAI_{SSP} that falls between 0 and 1. This parameter is the weighted sum of four sub-parameters which are related to the following aspects:

- the visibility of the plant (sub-parameter I_v);
- the colour of the plant compared to the colour of the immediate surrounding (sub-parameter I_{cl});
- the shape of the plant (sub-parameter I_f);
- the concurrence of various forms and types of panels in the same plant (sub-parameter I_{CC});

The percentage of each of these sub-indicators on the global indicator value is equal, respectively, to 64%, 19%, 9% and 8%. A climate indicator reduces the visibility and colour impacts depending on the weather conditions (e.g. good visibility, haze, precipitation, fog). From a first analysis of the OAI indicator, it can be noted that most of the aesthetic impact is attributed to the visibility and colour of the plant (over 80% of the overall indicator is represented by these sub-parameters) and given that the pictures are usually taken in good visibility conditions, in most of the times the analysis of the visual impact of a plant can be performed by means of the only four sub-parameters.

3. Calculations and results

The objective aesthetic impact of PV plants based on numerical indicators was conducted for the four photographs shown in

Figs. 1 and 2. 1 (left) and 2 (right). Two views of the 6 MW_p PV plant in Moorenweis (Germany).

Figs. 3 and 4. 3 (left) and 4 (right). Views of the PV plants of Seville and Herestried (Germany).

Figs. 1–4. The photographs shown in Figs. 1 and 2 refer to a photovoltaic system of 6 MW_p (over 34,000 modules of 175 Wp, one of the largest in Europe) ended in late 2007 at Moorenweis in Bavaria. The photograph of Fig. 3 refers to a 2 MW_p plant in Seville. The photograph of Fig. 4 refers to the Herestreid (again in Bavaria) 1.9 MW_p PV plant.

To determine the sub-parameter I_v the ratio of the total area occupied by the panels and the area of the landscape background A_{pl}/A_{ba} was calculated and expressed as a percentage, and is shown in Table 1, first column. From this quantity the impact indicator for visibility was calculated through the curve proposed by Torres Sibille et al. [4] that was determined through survey of ten experts and evaluators (the actual Eq. (1) of [4] was modified to fit to the curve represented in Fig. 1 of [4]). It reads

$$I_\nu = \begin{cases} -0.004x^2 + 0.128x & \text{for}\, x < 13.5 \\ 1 & \text{for}\, x > 13.5 \end{cases} \tag{1}$$

where x is the A_{pl}/A_{ba} percentage ratio. The I_v values obtained are reported in Table 1 and merely equals the unity in all the cases.

To determine the sub-parameter I_f, which refers to the plant form, the fractal dimensions D_f of the figures of the plants (subscript pl) and of the background (subscript ba) were calculated and are reported in Table 1. It is considered that the fractal dimension is indicative of the degree of artificiality of such artefacts in a natural landscape; the use of the fractal dimension in the impact analysis on the landscape is well established [19–21]. Once the contours were extracted from the photographs of the installations (for example, the contour of the picture of Fig. 4 is shown in Fig. 5) and exported into bitmaps, the fractal dimensions were calculated by means of the software Fractal Dimension v. 1.1 based on the box counting technique. The ratio between the fractal dimension of the plant and the one of the background, which can range from 0 to 2 for the definition of fractal dimension, is minimal for a $D_{f,pl}/D_{f,ba}$ equal to 1, while it grows for $D_{f,pl}/D_{f,ba}$ that tends to 0 or 2 (more steeply for values lower than the unity). The curve reported in [4], also in this case assessed through survey of experts, is

$$I_f = \begin{cases} 1 & \text{per}\, z = 0 \\ 100z & \text{per}\, 0 < z \le 0.01 \\ -0.085z + 1 & \text{per}\, 0.01 < z \le 0.75 \\ -3.745z + 3.745 & \text{per}\, 0.75 < z \le 1 \\ -1.048z^2 + 4.145z - 3.097 & \text{per}\, 1 < z \le 1.94 \\ 1 & \text{per}\, 1.94 < z \le 2 \end{cases} \tag{2}$$

where z is the ratio $D_{f,pl}/D_{f,ba}$. This curve was applied to determine the sub-parameters I_f reported in Table 1.

Table 1
Indicators and sub-parameters for the assessment of the visual impact, the form impact and the concurrence of various forms impact.

Indicators and sub-parameters Picture	A_{pl}/A_{ba} [%]	I_v [–]	$D_{f,pl}$ [–]	$D_{f,ba}$ [–]	$D_{f,pl}/D_{f,ba}$ [–]	I_f [–]	I_{CC} [–]
Moorensweis_1	14.6	1	1.960	1.956	1.0020	0.0041	0
Moorensweis_2	17.5	1	1.742	1.986	0.8852	0.4299	0
Seville	11.9	0.957	1.720	1.972	0.8722	0.4786	0
Heretsried	20.5	1	1.851	1.959	0.9449	0.2063	0

Table 2
CIELab colorimetric coordinates for the colour difference impact assessment, colour differences and sub-indicator for the colour difference impact.

Indicators and sub-parameters	PV			Vegetation/bright vegetation			Terrain/dark vegetation			$\Delta E^*_{PV,v}$	$\Delta E^*_{PV,t}$	ΔE^*_m	I_c
	L^*	a^*	b^*	L^*	a^*	b^*	L^*	a^*	b^*	[−]	[−]	[−]	[−]
Moorensweis_1	47	0	−14	47	−10	41	48	−14	34	55.90	50.01	52.96	0.1416
Moorensweis_2	92	−1	−2	28	−15	18	32	−8	19	68.50	63.95	66.23	0.1771
Seville PV bright	56	4	−14	–	–	–	75	12	25	–	44.11	50.86	0.1360
Seville PV dark	45	7	−24	–	–	–				–	57.60		
Heretsried	44	4	−11	40	0	37	83	9	25	48.33	53.31	50.82	0.1359

As regards the sub-parameter I_{CC}, it is considered that there are no significant differences in the forms used in the various plants (the one in Seville only has a colour difference) and therefore the sub-parameter for concurrence was assumed equal to zero (nonexistent impact) in all the cases as shown in Table 1.

There is no doubt that together with the visibility, the colour contrast is one of the most significant factors in assessing the compatibility of any artefact into the landscape. As for the impact due to the colour of the plant, the analysis of the work reported in various studies of landscape impact of various artefacts [22,14,9], and also in the case of Torres Sibille et al. [4], showed that a metric for measuring the colour difference should be selected. Following the cited literature, it was decided to measure the colour difference between the photovoltaic panel (as shown in the photograph due to lighting conditions, regardless of the actual colour) and its immediate surroundings. In all the studies, the use of the CIELab1974 formula for determining the colour difference, erroneously identified by some authors as colour contrast, was found. In the CIELab colour space (alternative to the colour space XYZ defined in 1931) a colour is identified by the triple of parameters (or colorimetric coordinates) hue L^*, saturation a^* and brightness b^*, and the difference between two colours can be expressed as the Euclidean distance between the two points that in the colour space represent the two colours, and is therefore

$$\Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \tag{3}$$

Since the CIELab space is uniform (equal distances correspond to equal differences in colour), Eq. (3), that was introduced for the first time in 1976 by CIE (International Commission on Illumination), should represent not only a distance between a colour and another, but also a variation in perception between a colour and another. However, further studies conducted mainly in the textile and automotive industry for very small colour differences, showed some local inhomogeneities in the perception in the CIELab colour space by the use of Eq. (3) and other formulations that express the colour difference, more complex than the one of Eq. (3) but more responsive to the human perception [23], were therefore developed by CIE in 1994 and 2000.

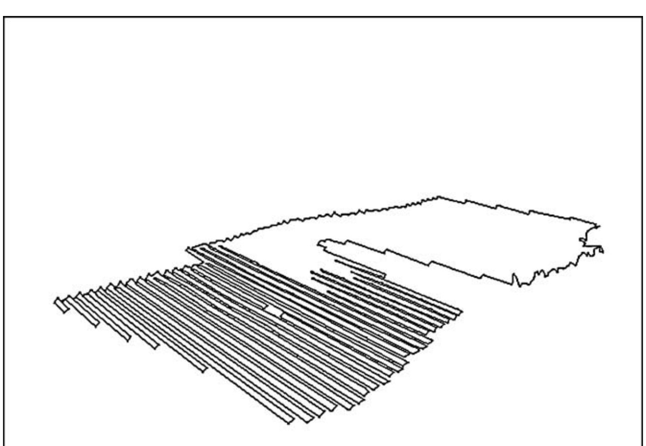


Fig. 5. Contour for the determination of the fractal dimension of the Moorenweis plant (picture of Fig. 2).

However, since in the case of landscape impact assessment, the colour differences are high, of the order of some tens of E^* (already for a value of ΔE^* of one unit, a difference between a colour and another can be perceived), it was deemed acceptable to use the CIELab 1976 colour difference formula, also because there is a strong variability of the coordinates between a point and the other in each image.

The colorimetric coordinates of the photovoltaic panels and of the immediate surroundings (sometimes divided into vegetation and soil if both are present) are shown in Table 2. In the case of the Seville picture two different colours of the photovoltaic panels are reported. It should be noted also that the coordinates L^*, a^* and b^* of photovoltaic panels are not the same or similar to those of the real object, but are affected by the lighting, visibility and reflection of the particular photograph.

From these coordinates, the colour differences ΔE^* were calculated by means of Eq. (3) and the average colour differences ΔE^*_m were determined when necessary. The transition from the average colour difference to the sub-parameter I_c was done assuming a maximum value of I_c, which is equal to 1 for the maximum ΔE^* (equal to 374 giving the fields of variability of the coordinates L^* a^* b^* equal to $0 < L^* < 100$, $-128 < a^* < +127$ and $-128 < b^* < +127$) and a zero I_c for a zero ΔE^*. The values of I_c obtained are report in Table 2.

From the values of the sub-parameters given in Tables 1 and 2, the index of aesthetic impact of a solar plant OAI_{SSP} can be determined as

$$OAI_{SPP} = 0.64 I_\nu + 0.19 I_c + 0.09 I_f + 0.08 I_{CC} \tag{4}$$

These values are reported in Table 3. By adopting a scale of the impact assessment based on 6 degrees (minimum for $0 < OAI_{SPP} < 0.1$; light for $0.1 < OAI_{SPP} < 0.3$, average $0.3 < OAI_{SPP} < 0.5$, significant for $0.5 < OAI_{SPP} < 0.7$, very significant for $0.7 < OAI_{SPP} < 0.9$ and maximum for $0.9 < OAI_{SPP} < 1$, similarly to the scale proposed by Tsoutsos et al. [7] for the impact indicator of wind turbines) all the visual impacts but the one of Fig. 2, which is very significant, fall into the same impact category. The comparison between the values that the sub-parameters and the global OAI_{SPP} parameters assume is done in Fig. 6, where the values that the sub-parameters and the parameter of main effect in each case taking the graph of Fig. 6.

Table 3
Objective aesthetic impact indexes for the PV plants of Figs. 1–4.

	I_c [−]	Impact scale
Moorensweis_1	0.6673	Significant
Moorensweis_2	0.7123	Very significant
Seville PV bright	0.6814	Significant
Heretsried	0.6844	Significant

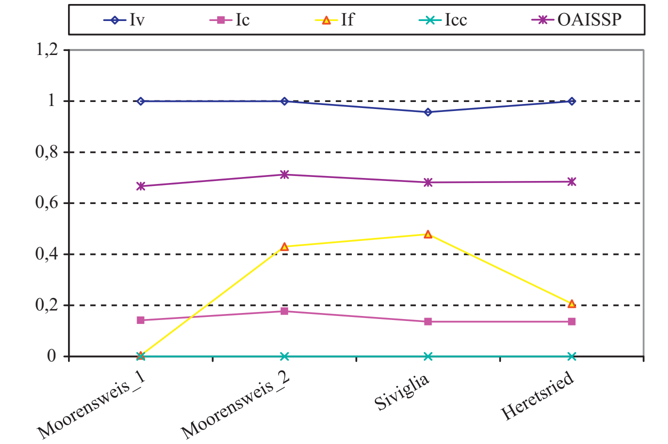


Fig. 6. Comparison between the OAI_{SSP} parameter and the sub-parameters for the four case studies.

4. Discussion of the results and conclusions

The procedure for evaluating the visual impact of photovoltaic plants based on the OAI_{SSP} indicator can be, on the overall, easily and quickly implemented. However, some problems arise; these are:

- in the case of its use at the planning and design stages, it is essential to obtain a good visual simulation of the plant: this is important only from the point of view of the shape of the plant, that can be easily reproduced by means of a 3D drawing tool, but especially from the point of view of the colours that, as said before, are not coincident with the ones of the object;
- in case of its use for verification of the visual impact of an existing plant, the procedure is affected by the conditions with which the photograph was taken (distance, lens, focus, atmosphere, sky cover, reflection, etc.)

With reference to those two points, further research activity should be carried out to verify how it is possible to reproduce the real colours that arise in a picture with design simulation tools (rendering options), how much the results are affected by the degrees of freedom of the picture/simulation and what are the procedures that should be taken in order to minimize the effects of such aspects.

However, the use of such a procedure allows the design criteria that can guide the design of a photovoltaic plant (as well as a solar thermal plant) towards a better landscape compatibility, to be identified. These criteria should be taken into consideration at the same time with the most important design criterion for a photovoltaic plant, that is a design optimized to maximize the solar collection from the energy point of view. This last criterion involves the adoption of particular tilt and azimuth angles of the sun-catching surfaces that are related to the latitude of the location, the period of time of analysis and the climate conditions, and should be carefully selected.

That said, the analysis of the visual impact carried out by means of visual images, suggests to minimize the area occupied by the plant with respect to the area of the landscape background; in the case of large systems of some MW of peak power, where the area is extensive, it is therefore desirable to find some screens between the viewpoints and the plant to reduce the visible area of the PV without reducing the solar energy that reaches the surfaces of the plant.

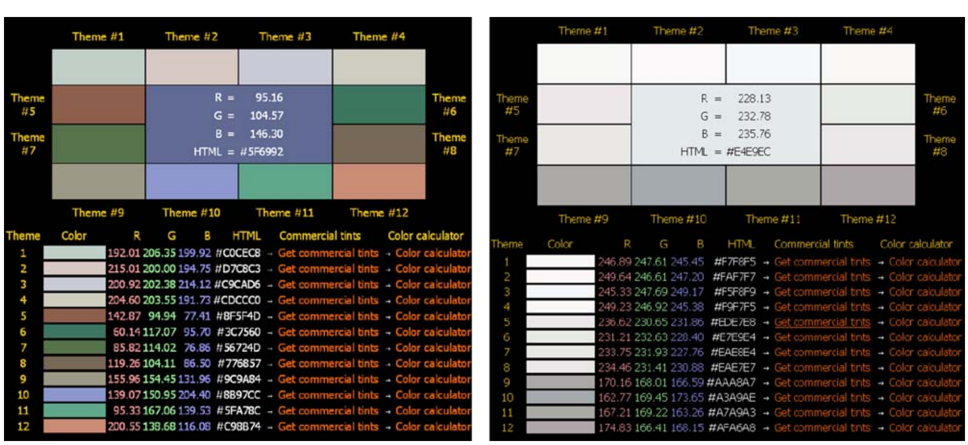
As regards the shape of the objects that constitute the plant, in the case of rigid PV modules, there are not margins of intervention; vice versa, next generation thin film solar cells (amorphous silicon, tellurium cadmium or organic cells) can take various shapes and can contribute to lower the impact due to the concurrence of various forms.

As regards the colour, given that unless coloured photovoltaic cells, that have a lower yield, are used, it is very difficult to decrease the colour difference between the PV and the surroundings, the design possibilities associated with the use of colour harmonies appear promising. These colour harmonies are sets of colours that are similar or complementary to that of the PV, as it is perceived by the observer, and can be determined through some applications that perform the similarity and complementary colour rules and calculations. An example of these colours is reproduced in Figs. 7 and 8 where the colours are shown for the cases of Seville and Moorensweis_2.

Finally, the application of the OAI_{SSP} suggests that it is appropriate to use a single type of modules within the same PV plant (frequently, this is not the case of self-made plants, for example in Fig. 9), and in any case within the same view, in order to avoid the disturbance of vision due to the competition of different types of modules (as it happens for solar static and solar tracking modules placed together).

As regards the application of an objective visual impact assessment procedure, as the OAI_{SSP} is, to the authorization of project developments of PV plants, some consideration can be made.

First, the authority should clearly define a regulatory framework where the viewpoints from which the visual simulation of



Figs. 7 and 8. 7 (left) and 8 (right). Colour harmonies of analogous and complementary colours (colour coordinates are here expressed in the RGB system) with respect to the PV colours of Seville (left)and Moorenweis_2 (right). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

Fig. 9. Various forms and colours of a PV plant for an alpine shelter in France (Vallée Etroite). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of the article.)

the PV plant should be taken, the representation rules, focus, etc. are clearly defined. This may seem quite difficult at first, but it should be noted that in many hill or mountain local communities this is feasible and allows better results than the use of GIS tools for each project development.

The viewpoints may be determined once, by means of a visibility analysis made by GIS and based on the criteria selected by the authority (population density, historical sites, preservation of identities, etc.). The decision about these criteria cannot be taken by a technician, but is eminently social and political. Once that the viewpoints will be selected, then for each PV plant installation .only the design simulation should be made and analyzed by means of a procedure as the OAI_{SSP} tool, or a simpler version as it was proposed in this article. In fact, the application of methodologies that are extensive type (see paragraph 2), may not be appropriate for the reasons of costs and competences involved, in case of small and medium size projects.

Such a procedure has also the advantage of being objective, while frequently in practice the aesthetic and landscape impact assessment is evaluated by means of judgments of the technician on visual simulation. The objective feature of the tool may serve also to the designer to clearly evaluate the impact of a project before the regulatory authorization stage.

Furthermore, a tool based on the objective visibility analysis for the visual impact assessment may be used also in case of building integrated PV plants. Further research activity is currently being carried out to verify the application of the modified OAI_{SSP} tool to the BIPV plants.

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